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Non-equilibrium Kinematics in Merging Galaxies

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Abstract. Measurements of the kinematics of merging galaxies are often used to derive dynamical masses, study evolution onto the fundamental plane, or probe relaxation processes. These measurements are often compromised to some degree by strong non-equilibrium motions in the merging galaxies. This talk focuses on the evolution of the kinematics of merging galaxies, and highlights some pitfalls which occur when studying non-equilibrium systems.

1. Evolution of Velocity Moments in Merging Galaxies

The global kinematics of merging galaxies are often used to infer dynamical masses, or study evolution of merger remnants onto the fundamental plane (e.g., Lake & Dressler 1986; Shier *et al.* 1994; James *et al.* 1999). In systems well out of equilibrium, these measurements may not yield true estimates of the velocity dispersion of the system. For example, in a merger where the nuclei have not yet coalesced, much of the kinetic energy of the the system may be in bulk motion of the nuclei, rather than in pure random stellar motions. Such conditions could in principle lead to systematic errors in dynamical masses or fundamental plane properties. Equally important is the timescale over which any merger-induced kinematic irregularities are mixed away through violent relaxation or mixing.

To examine the evolution of the kinematic moments of a galaxy merger, Figure 1 shows the projected velocity moments in an N-body model of an equal mass galaxy merger. The data is constructed to simulate observations with modest spatial resolution of ~ 1 kpc. The low order moments of the velocity distribution very quickly evolve to their final value – violent relaxation in the inner regions is extremely efficient. Even during the final coalescence phase, the velocity dispersion of the merger is essentially unchanging, except for extreme situations where the remnant is viewed almost exactly along the orbital plane. This analysis suggests that studies which place mergers on the fundamental plane are not excessively compromised by possible kinematic evolution of the remnants; instead, luminosity evolution should dominate any changes in the properties of the remnant.

At larger radius, the merger remnant possesses a significant rotational component, as transfer of orbital angular momentum has spun up the remnant (e.g., Hernquist 1992). The higher order velocity moments (skew and kurtosis) continue to evolve for several dynamical times, particularly in the outer portions of the remnant where the mixing timescale is long. These higher order moments also vary significantly with viewing angle, reflecting the fact that the merger

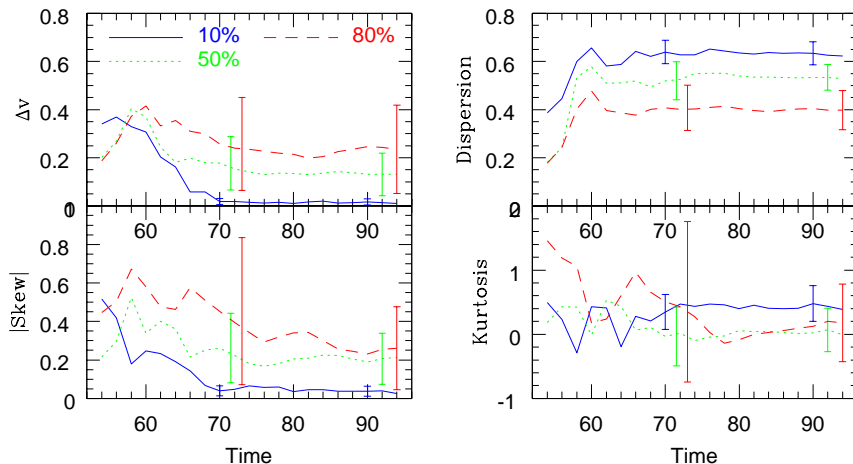


Figure 1. Evolution of the projected velocity moments during an equal mass merger. The three curves show local measurements at radii containing 10%, 50%, and 80% of the total stellar mass of the system; “error bars” show the variance of the measured moments due to viewing geometry. Δv is the velocity difference between the opposite sides of the galaxies. The nuclei are separated by ~ 5 kpc at $T=60$, and coalesce at $T=70$. To scale to Milky Way-type progenitors, unit time is 13 Myr and unit velocity is 250 km/s.

kinematics maintain a “memory” of the initial orbital angular momentum. As high angular momentum material streams back into the remnant from the tidal debris, incomplete mixing results in extremely non-gaussian line profiles.

2. Local Stellar Kinematics and Ghost Masses

On smaller scales, however, measurements of local velocity dispersion can give erroneous results if the system has not yet relaxed. Figure 2 shows the merger model “observed” at higher spatial resolution at a time when the nuclei are still separated by a few kpc. Looking along the orbital plane, the nuclei still possess a significant amount of bulk motion. Measured on small scales, this bulk motion shows as a gradient in the projected radial velocity across the two nuclei. Perhaps more interesting is the rise in projected velocity dispersion between the nuclei, where the velocity profile shows a single broad line with dispersion $\sim 30\%$ higher than in the nuclei themselves. A similar rise is seen between the nuclei of NGC 6240 (Tezca *et al.* 1999 in prep, referenced in Tacconi *et al.* 1999), where a central gas concentration exists. The simulations here indicate that such features can arise in double nucleus systems even when no central mass exists, and suggest that dynamical masses inferred this way can be significantly overestimated.

In this case, the full analysis of the line profiles results in a better understanding of the dynamical conditions. The gradient across the nuclei again is an indicator of large bulk motions, and the shape of the line profile is rather flat-topped (negative kurtosis), exactly what is expected from the incomplete blending of two separate line profiles. Here, of course, the increase in velocity

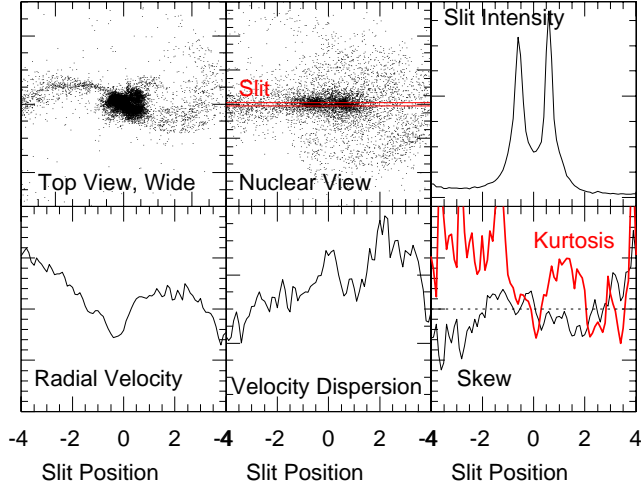


Figure 2. Simulated longslit velocity moments for an unrelaxed merger; the nuclei are in the final stages of coalescence. Unit length is ~ 3.5 kpc.

dispersion is due simply to the projected overlap of the nuclei, but the complete line profile is needed to unravel the complex dynamics.

3. Ionized Gas Kinematics and Starburst Winds

Finally, while gas kinematics are perhaps the easiest to measure, they give the most ambiguous measurement of the gravitational kinematics of a merging system. Aside from the problems of the evolving gravitational kinematics and line-of-sight projection effects, gas kinematics are also subject to influences such as shocks, radial inflow, and starburst winds. All of these conspire to make a very confusing kinematic dataset.

A case in point is the ultraluminous infrared galaxy NGC 6240. This starburst system has a double nucleus separated by $\sim 1.5''$ and is clearly a late stage merger. Based on $H\alpha$ velocity mapping of this system, Bland-Hawthorn *et al.* (1991) proposed that a $10^{12} M_{\odot}$ black hole exists well outside the nucleus, at a projected distance of 6 kpc. The major piece of evidence supporting this claim was a sharp gradient in the ionized gas kinematics, suggestive of a rapidly rotating disk.

To study this object in more detail, we (van der Marel *et al.* in prep) have initiated a program using HST to obtain imaging and longslit spectroscopic data for the inner regions of NGC 6240. Figure 3 shows an F814W image of the center of NGC 6240, along with a narrow band image centered on $H\alpha + [NII]$ (taken using the F673N filter, which for NGC 6240 fortuitously sits on redshifted $H\alpha$). The narrow band image shows a clear starburst wind morphology in the ionized gas.

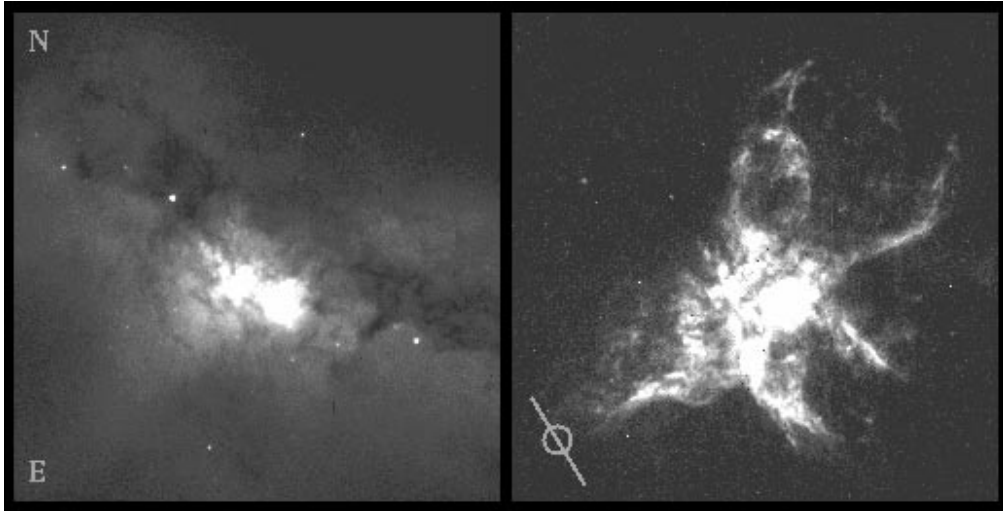


Figure 3. Left: F814W image of the center of NGC 6240. Right: Narrow band $H\alpha$ image. The position of the reported $10^{12}M_{\odot}$ black hole (Bland-Hawthorn *et al.* 1991) is shown, along with the position angle of the purported disk surrounding it.

Overplotted on Figure 3b is the position of the putative black hole, along with the position angle of the observed velocity gradient. Interestingly, the position lies directly along an ionized filament from the starburst wind, with the kinematic gradient directed orthogonal to the filament's direction. While our narrow-band data do not go deep enough to study the detailed distribution of ionized gas immediately surrounding the proposed black hole, the image certainly suggests that the observed kinematics may be strongly influenced by the starburst wind, indicating that the black hole may not be real. The strong gradient that was attributed to a black hole may instead be due to kinematic gradients in the starburst wind, or even simple geometry of the wind filament projecting on top of background system emission. We have follow-up STIS spectroscopy planned to further study the complex kinematics in this intriguing system.

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